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RESOURCE REQUIREMENTS FOR INDUSTRIAL PROCESSES: A WELMM COMPARISON OF ENERGY CHAINS

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PREFACE

When developing a new method of analysis, it is difficult but nonetheless very important to maintain a fair balance between the method itself (and/or its tools) and its possible utilization. From the early years of development of the WELMM method by the small research group working on resources at IIASA, we have always tried to balance these two aspects. In fact, only utilization or application of the method can demonstrate its interest, possible if it is appropriately developed.

Applications of the WELMM approach are numerous and varied: at the local, regional or global level; oriented towards processes (for comparison) or a combination of technologies; for energy (the initial purpose) and non-energy fields; for the short term, or for the long term, etc. We have at IIASA already implemented some of these potential applications--and we hope that there will be more performed, both in-house and in other organizations--and we have greatly benefited from carrying out these applications, as valuable feedbacks to the method itself and to our task.

This report presents the results of applying the WELMM approach, through the use of the WELMM Facility Data Base, to the comparison of various energy chains, based on coal, natural gas, nuclear and solar resources/technologies. This exercise has been a very valuable training for us, but we hope that the results will also be interesting for others. They show the WELMM resource requirements necessary to achieve a similar objective using very different resources and techniques.

The "energy chains" approach has been broadly used, mainly for economic comparisons. Its main limitation is that the chains considered are generally specific and do not necessarily relate to real cases. This is why it is generally a first step and is often extended to real case scenarios (which have, in fact, been developed at IIASA).

As such, these analyses constitute one of the first applications of the WELMM method developed at IIASA and illustrate some of its potential.

Michel Grenon

ACKNOWLEDGEMENTS

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I would like to take the opportunity to thank all the people and organizations (CEA, CNRS, EdF in France and Professor Astakhov from the U.S.S.R.--just to name a few), whose interest in the WELMM method and its applications and whose help with supplying data made our work possible.

Finally, I would like to thank Professor Grenon for his continued support of my work at IIASA.

ABSTRACT

This paper presents an application of the WELMM method to the comparison of various energy chains. It can be divided into two main parts:

--the comparison of energy chains at the secondary energy level (four coal, three nuclear and two solar electricity producing chains with an annual output of 6.1 TWh each, are studied);

--the comparison of energy chains at the useful energy level (for a defined output of 0.65 Mtce useful energy three alternative chains are studied: coal-electric, synthetic natural gas, and liquefied natural gas).

More disaggregated data on the nuclear and solar electricity producing chains are presented in the Appendix.

CONTENTS

INTRODUCTION

In assessing energy strategies the systems aspects and interrelationships between energy and other natural and/or human resources have to be taken into account.

As energy resources are generally not used in their primary state (crude oil, uranium etc.) they have to be processed in industrial/energy installations in order to be available to the final consumer. All these installations or industrial/energy facilities require, in addition to their primary input, natural and human resources. Furthermore, the use of natural resources can interfere with other possible uses of the same resources (e.g. land requirements for surface mining operations can conflict with agricultural land use. Cooling and process water requirements can conflict, in areas with a scarce water supply, with water demand for irrigation or urban needs).

It is therefore important to bring some insight into these resource requirements and to analyze a given resource processing system through its needs accounted in physical terms. These requirements can then be compared with the availability of resources and a better understanding of their possible interactions or substitutions can be reached. In addition, qualitative criteria, such as social acceptability and environmental impacts etc., should complete a systematic analysis of a given resource strategy. An energy processing system can be represented by a combination of various industrial processes (representing installations or facilities), which are necessary to go from the primary resource to the secondary or final level where the processed primary resource is consumed. Each of these industrial units can be schematized as in the process scheme in Figure 1.

An energy chain will therefore be defined as: *the set of industrial/energy facilities which cover all the processes to harvest, transport and convert a primary to a secondary, final or useful energy source.*

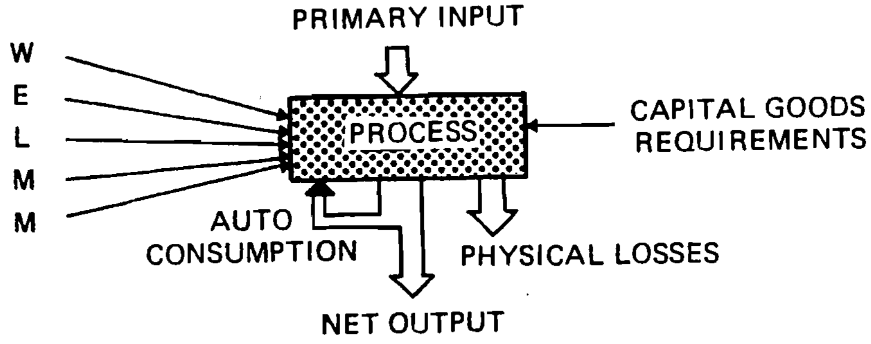

Figure 1. Process analysis

Depending on the level of aggregation, the following steps are generally distinguished to describe an energy processing system: extraction, transportation, processing, distribution, storage, conversion and management of final waste [1,2]. These steps describe a general framework which can be adapted to the various energy resource processing systems.

As examples of the different levels of complexity the nuclear and solar electricity chains are described in Figure 2. In both chains the output is the same: electricity. This already leads us to the first possible application of the WELMM approach in comparing various energy chains which produce the same amount of *secondary energy* (or, including the transport and distribution of electricity, the same amount of *final energy*). This will be dealt with in the first part of this paper.

In any case this analysis does not take into account the different supply options possible to satisfy the various *useful energy* needs (or services required) such as low grade heat (heating, hot water, cooking etc.) where a competitive market of various energy forms exists (use of oil/gas, solar or electricity) at the *final energy* level. Due to the varying efficiencies of end-use appliances (solar flat collectors, oil fired heating, electric heat pumps etc.) the quantity of *final energy* required to deliver the same amount of useful energy varies. The second part of this paper concentrates on the comparison of different supply options which provide the same service (or the same quantity of useful energy) to the consumer.

THE CRITERIA FOR ENERGY CHAIN COMPARISONS: "WELMM"

In comparing various energy supply options several methods have been used extensively: classical economic analysis, environmental impact assessment, energy analysis--these are only the main ones. All of them have the tendency to be either

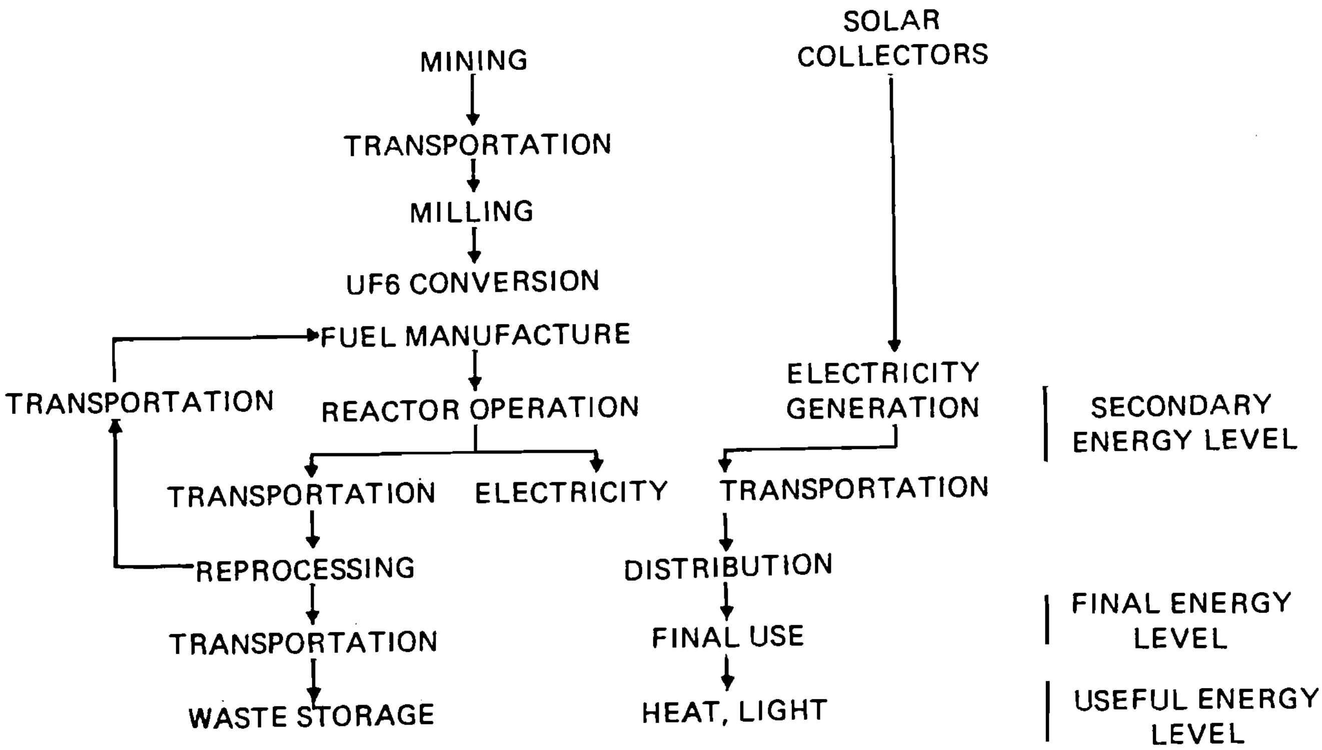

Figure 2. Nuclear and solar thermal electricity chains

single-criterion (environmental, energy analysis) or single attribute (economic analysis), they thus withstand systematic analysis of a resource strategy by looking at a single resource alone without giving indications about possible shifts from one scarce resource (energy) to another (certain materials, land and water). Resource strategies therefore have to be evaluated with a multicriteria, multiattribute approach, preferably using physical quantities of resources which can then be checked with their availability.

This physical resource accounting is the purpose of the WELMM (Water, Energy, Land, Manpower and Materials) approach [3] which analyzes resource requirements of a resource processing system through the use of computerized data bases. The main tool for the evaluation of the resource requirements of industrial processes or facilities is the WELMM Facility Data Base (FDB). In this data base general characteristics of industrial/energy facilities or installations as well as the resource requirements for the construction and operation of these facilities are recorded [4]. In fact the WELMM approach introduces additional aspects to economic analysis, energy analysis and, to some extent, environmental analysis, and can provide a good basis for systematic analysis of a given resource strategy, especially in the long-term context when economic data are unreliable. In the data bases, which are the tools of the WELMM method, economic data--although not the main objective--are nevertheless included; energy and environmental data (quantitative and qualitative aspects of water, land and materials e.g. wastes) as well as qualitative indicators for the human resource requirements (critical skills required, type of work etc.) enlarge the scope of the purely physical quantity oriented WELMM data to a more systematic multicriteria understanding of a given resource strategy.

If a WELMM analysis is carried out carefully it should come to the same conclusions as an economic assessment, but with the advantage that physical quantities are not likely to fluctuate as much as financial data in a given economic context, and therefore the range of uncertainty of an analysis can be reduced.

One important aspect of this accounting process is the definition of the boundaries of the system analyzed: within the WELMM method we distinguish between two levels of resource requirements:

a) *The direct requirements:* the resource requirements used directly on site for the construction and operation of a facility, such as water, fuel, electricity, structural steel or metal contained in prefabricated equipment and machinery imported on site.

b) *The indirect requirements:* for the direct resource requirements (steel, aluminium) the same concept of industrial processes and chains is applied as for the energy chains. The results from this evaluation of the steel chain (etc.) give in return the indirect requirements of our energy chains.

The advantage of differentiating between the direct and indirect requirements is that is enables long term projections or scenarios of changing resource intensiveness of various technologies (e.g. decreasing ore grade for primary metal production, introduction of new technologies such as direct reduction in steel fabrication etc.). It is thus more flexible than existing analysis techniques such as input-output coefficients, which tend to reflect present or even past resource intensiveness (there is generally a time lag of five years between the original data and the use of coefficients calculated from them in models).

The methodology for evaluating the indirect resource requirements is defined and has proved feasible in first applications [5,6], but the amount of data involved* is very important and therefore input-output techniques have been used at IIASA to determine indirect resource requirements [7]. From these results a detailed indirect WELMM analysis for the most sensitive materials will be carried out.

The comparisons presented in this paper concentrate on the direct resource requirements of energy chains. The results of an evaluation of the indirect requirements will be published. However, at present the results are too preliminary to be included in this paper.

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*Similar chains as in this paper for energy would have to be evaluated with their associated industrial facilities for all main equipment and material items.

WELMM COMPARISON OF ELECTRICITY PRODUCING CHAINS

Table 1 summarizes the main steps and basic assumptions made in order to consider four coal, three nuclear and two solar electricity chains. Each chain includes the various facilities, or share of facilities, associated with the production of 6.1 TWh (6.1 10^9 kWh) electricity per year--corresponding to the output of a 1000 MW power plant with 70% load factor. A lifetime of 30 years was assumed for all facilities.

The power plants were assumed to be located near main consuming areas which would not necessitate long distance transportation of electricity. The electricity distribution network would be the same for the different electricity generating chains, and therefore the WELMM comparison of the chains relative to each other was carried out at the secondary energy level excluding the transport and distribution of electricity.

The energy chains were determined by choosing representative examples from the Facility Data Base. Some of the data compiled in the WELMM FDB relate to standard types of energy facilities such as power plants (coal fired in the 600 to 1000 MW range, solar 100 MW STEC--Solar Thermal Electric Conversion--modules etc.), transportation facilities (such as unit trains of 10000 tons or slurry pipelines of 1500 km) etc.

It is obvious that for some facilities (i.e. those related to mining operations) it is impossible to define "typical" examples and this is the reason why exhaustive WELMM studies were carried out. From this analysis, sample data were chosen for the comparison.

However, it must be stressed that the chains chosen are illustrative examples rather than descriptions of the coal, nuclear or solar energy chains. Although they reflect general

Table 1. Characteristics of electricity producing chains (output: 6.1 Twh/yr).

	COAL 1	COAL 2	COAL 3	COAL 4	LWR 1	LWR 2	FBR	SOLAR 1	SOLAR 2
HARVESTING	ROOM AND PILLAR UNDERGROUND MINE US. WESTERN TYPE SEAM THICKNESS: 1.5 m		STRIP MINE US. WESTERN TYPE SEAM THICKNESS: 9.2 m		60% SURFACE 40% UNDERGROUND ORE: 0.203% U_3O_8	ROOM AND PILLAR UNDERGROUND MINE ORE: CHATTANOOGA SHALE 0.007% U_3O_8		———	———
FUEL PREPARATION	COAL PREPARATION (CRUSHING AND SCREENING)				MILLING CONVERSION ENRICHMENT FUEL FABRICATION		MILLING FUEL FABRICATION	———	———
TRANSPORT	RAIL 900 km	SLURRY PIPELINE 900 km	RAIL 900 km	SLURRY PIPELINE 900 km	NEGL.	NEGL.	NEGL.	———	———
POWER PLANT	1000 MW CONVENTIONAL 70% LOAD FACTOR	1000 MW FLUIDIZED BED 70% LOAD FACTOR	1000 MW CONVENTIONAL 70% LOAD FACTOR	1000 MW FLUIDIZED BED 70% LOAD FACTOR	1000 MW PWR 3.2% ENRICHED URANIUM FUEL 70% LOAD FACTOR		1000 MW LIQUID METAL FAST BREEDER PU/U238 FUEL 70% LOAD FACTOR	28 X 100 MWe STEC DIRECT RADIATION 1500 hrs/yr 1500 kWh/m²/yr	14 X 100 MWe STEC DIRECT RADIATION 2700 hrs/yr 3000 kWh/m²/yr
ELECTRICITY STORAGE	———	———	———	———	———	———	———	6 HOURS THERMAL STORAGE ON SITE	
REPROCESSING	———	———	———	———	URANIUM REPROCESSING		URANIUM AND PLUTONIUM REPROCESSING	———	———
WASTE STORAGE	NEGL.	NEGL.	NEGL.	NEGL.	LOW LEVEL WASTE STORAGE TEMPORARY (MAX. 100 yrs) HIGH LEVEL WASTE STORAGE			———	———

trends in each technology quite well, the figures are also a result of the definition of the chains (i.e. location of the solar power plants, mining conditions, heat content of coal etc.). Thus, although we have tried to choose representative examples one has to bear in mind the definitions of these chains in interpreting the results.

MAIN CHARACTERISTICS OF THE COAL CHAINS

There are two main differences in the four chains studied.

Coal Chains 1 and 3:

correspond to actual technology with conventional coal fired power plants (thermal efficiency of 37.8%) and coal transportation over 900 km by rail.

Coal Chains 2 and 4:

represent advanced technology with atmospheric fluidized bed power plants (thermal efficiency: 35.7%) and coal slurry pipeline transportation. Particulate and sulfur dioxide emissions are drastically reduced and one can therefore speak of "environmentally controlled chains."

Furthermore, the chains differ depending on the sample of mines chosen. Generally coal is mined under fairly favorable conditions, such as those prevailing in the western part of the United States.

Coal Chains 1 and 2:

coal is mined in underground mines using the room and pillar method; the seam thickness was assumed to be 1.5 meters.

Coal Chains 3 and 4:

the mine considered is a U.S. western type strip mine with a 9.2 m seam and a stripping ratio of 2.1:1 (yd^3/short ton).

In all chains coal was assumed to be high quality bituminous coal; each chain also includes a coal preparation facility (crushing and screening) with a run of mine to clean coal ratio of 1.3:1.

MAIN CHARACTERISTICS OF THE NUCLEAR CHAINS

The two main types of nuclear technology have been considered: a LWR and a FBR chain, each of them consisting of the power plants and the necessary facilities of the associated nuclear fuel cycle. The LWR chains comprise pressurized water reactors of 1000 MW with natural draft wet cooling towers, LWR fuel fabrication, uranium enrichment (gaseous diffusion), uranium conversion as well as LWR spent fuel reprocessing, land burial facilities for low level waste and a temporary high level waste storage facility (water basin concept).

LWR1:

60% of required uranium is produced in surface mines and 40% in underground mines (corresponding to the present U.S. supply) and processed in a uranium mill The ore contains 0.203% U_3O_8 (U.S. average 1976) or 1720 ppm U-metal.

LWR2:

In this chain low grade Chattanooga shale (0.007% U_3O_8 or 60 ppm U-metal) is mined in an underground room and pillar mine and processed in an associated uranium shale mill [8]. This chain clearly does not reflect the short term perspectives of uranium mining but would probably have to be considered in the long term. In any case it represents an extreme case as the quantity of uranium ore to be mined reaches the order of magnitude of the quantity of coal to be extracted in order to produce the same amount of electricity.

The FBR Chain

Here a Liquid Metal Fast Breeder Reactor of 1000 MWe with natural draft wet cooling towers and a thermal efficiency of 40% along with the necessary facilities of the fuel cycle were considered. The fuel cycle is less complex than in the LWR chain and consists of FBR fuel fabrication and reprocessing facilities as well as low and high level waste storage. For the LMFBR chain it was assumed that only a small quantity of uranium has to be mined and milled, produced from a uranium shale (60 ppm) deposit as in the LWR2 case. Most of the uranium required is U238, recovered from depleted LWR enrichment tails. No WELMM impacts were accounted for in the case of plutonium as this is a by-product of LWR fuel reprocessing. Thus the mining impacts for the LMFBR chain are drastically reduced.

For all nuclear chains the transportation of the nuclear fuel has been neglected in view of the small quantities involved, which represent a safety problem rather than a significant resource requirement. In the Appendix more disaggregated WELMM requirements for the three nuclear electricity chains are presented in order to give insight into the mining impact of these chains.

THE SOLAR CHAINS

Electricity is produced in 100 MWe STECs, with associated 6 hour thermal storage, which produce electricity for intermediate demand. (In Table A-3 in the Appendix, more details on the WELMM requirements for a 100 MW STEC module are given).

Solar Chain 1:

these STECs would be located in Southern France (radiation during 1200 hours/year with 1500 kWh/m^2 year). Depending on whether one considers a doubling of the STEC modules or simply a doubling of the heliostat fields compared to the STECs in the Solar 2 chain, a range of data are presented in the WELMM analysis.

Solar Chain 2:

this corresponds to a facility in Southern California (radiation during 1500 hours per year and 2500 kWh/m^2/year).

To produce 6.1 TWh, 28 or 14 100 MWe STECs are required respectively.

WELMM ANALYSIS

Water

In WELMM terminology, *water intake* corresponds to the water withdrawn from the environment; *water consumption* is the fraction of the water intake not restituted to the environment (e.g. water evaporated in cooling towers or settling ponds or consumed in a chemical process). *Water discharge* is the amount of water restituted to the environment after use although it might be polluted (physically and/or thermally).

As one can see from Table 2, the biggest water users are by far the nuclear LWR chains; this is mainly due to greater quantities of waste heat that have to be cooled off. The FBR water intake is, due to the higher thermal efficiency, considerably lower, and can be compared to the water intake for coal-fired power plants. The solar STECs equipped with dry cooling towers require only small water quantities for circuit replacement and for the cleaning of the heliostats. In this case all the water intake is also consumed, whereas for the coal and nuclear chains between 30% to 40% of the water intake is discharged after use, mainly as cooling water.

It is interesting to note that in the technologically advanced coal chains (COAL 2 and COAL 4) the overall water intake is lower than in the conventional coal chains, although coal is transported with slurry pipelines, an extensive water consumer. The reason for this is that advanced fluidized bed power plants have about 20% less water intake [9] than conventional power plants and the water requirements for the slurry pipeline correspond to only 10% of the total water requirements of the chain. In addition the water output from the slurry dewatering plant can be used as cooling water for the power plant, thus resulting in a 20% reduction in water consumption for the technologically advanced coal chains. One can conclude from this that although water supply problems might occur for big coal slurry pipeline projects in arid regions, the most sensitive figure for water requirements of coal chains is the cooling water intake. Any improvement in these requirements can offset the additional water requirements due to coal slurry transportation if the whole coal energy chain is considered.

Energy

The figures as presented in Table 2 correspond to the direct energy requirements for operation only. The motor and process heat fuel requirements have been converted to kWh equivalent on the basis of the thermal equivalent of electricity (1 kWh = 860 kcal), in order that total operational energy requirements be comparable with the output of the energy chains. For the solar and LMFBR chains no sufficiently reliable data were available to allow definitive conclusions. Therefore it was decided not to present the energy data for these chains. In any case, for the LMFBR chain the energy requirements should be lower than in the LWR1 chain, as the mining impact is considerably lower and the fuel cycle less complex (no enrichment necessary); see also Table A-2 in the Appendix.

For the LWR2 chain using 60 ppm ore, information on energy requirements is poor; therefore a range of data (varying between 6.7 and 17.5% of the energy produced) is presented. The uncertainty is mainly due to a wide range of data for the uranium shale milling process (the highest estimates resulting in 1076 10^6 kWh equivalent [8]). An intermediate value of about 600 10^6 kWh equivalent (or about 10% of the energy produced) could be considered as a more realistic estimate for the energy requirements of the LWR2 chain.

In the LWR1 case the energy requirements are mainly due to the uranium enrichment (consuming about 5% of the energy output of the chain). As the data presented corresponds only to the direct operational energy requirements, they represent consequently only a fraction of the total operational energy needs. If the energy embodied in the materials required for

Table 2. Water, Energy, Land and Manpower requirements for electricity producing chains (output: 6.1 Twh/yr).

	COAL 1	COAL 2	COAL 3	COAL 4	LWR 1	LWR 2	FBR	SOLAR 1	SOLAR 2
WATER INTAKE in 10^6 m^3/yr	19.2	18.0	18.9	17.7	29.4	29.7	19.4	0.2	0.1
ENERGY FOR OPERAT. in 10^6 kWh/yr*									
ELECTRICITY	81.6	172.9	42.5	131.2	293.0	343.9–395.6	?	?	?
MOTOR AND PROCESS HEAT FUELS	205.6	67.0	225.4	87.9	58.9	>69.1–680.4	?	?	?
TOTAL	287.2	239.9	267.9	219.1	351.9	413–1076	?	?	?
IN % OF ANNUAL PRODUCTION	4.7%	3.9%	4.4%	3.6%	5.7%	6.7%–17.5%	?	?	?
LAND IN km^2									
FIXED USE	1.1	1.8	1.0	1.8	1–1.5	>1–1.5	>1.5	108.6	54.3
OUT OF IS PERMANENT	0	0	0	0	0.6	0.6	>0.6	0	0
MINING/YEAR	0.43	0.48	0.23	0.25	0.07	1.1	NEGL.	0	0
NON EXCLUSIVE FOR TRANSPORT OVER 900 km**	11.3	28.3	11.3	28.3	NEGL.	NEGL.	NEGL.	–	–
MANPOWER IN MAN-YEARS									
CONSTRUCTION	3570	4000–7500	3784	4000–7500	6755	>6827	7462	30800–47600	23800
OPERATION/YEAR	1325	1156	652	467	245	464	142	?	?
OUT OF FOR MINING	817	866	167	177	53	273	2	0	0

*Motor and process fuels have been converted into kWh on basis of 1 kWh = 860 kcal

**This is the total area required for a rail track or slurry pipeline over 900 km operation (e.g. sulfuric acid for the uranium milling, replacement parts for the facilities) were to be included, the operational energy expenses would amount to about 8% of the energy produced in the LWR1 chain. In order to complete an energy analysis, the direct energy required to construct the facilities for the energy chain and the energy consumed for the fabrication of the materials required to construct these facilities would have to be added. For the LWR1 chain the total energy required for the construction and operation of the chain would be around 11.5% of the energy produced (direct and indirect construction energy requirements divided by the lifetime, plus the annual direct and indirect operational energy requirements).

In the four coal chains the energy is mainly required for the mining and the transportation of coal. It can be concluded that transportation via slurry pipeline and surface mined coal are more energy efficient than alternative systems. Consequently a combination of both (COAL 4) is the less energy-consuming chain.

Land

For the land requirements as presented in Table 2 the following definitions were used. *Fixed land use:* this is the area required for the sites of the power plants and the necessary fuel cycle installations. This land is used during the lifetime of the facilities and can be re-used for other purposes after the destruction of the installations. In the case of the nuclear chains a fraction of the fixed land use is restricted for other uses even after the lifetime of the facilities (core area of nuclear reactors, high radioactive zone of reprocessing plants); or is required for a time period exceeding the lifetime of the fuel cycle facilities (area for waste storage). We therefore speak of *permanent land use*. For the transportation facilities, where we require only a fraction of the total capacity and where the land use for energy purposes does not exclude other uses (passenger transport by rail, agricultural land use over underground pipelines or in Right of Way land) one speaks of *non-exclusive land*. The fixed land use and the annual mining impact cumulated over the lifetime of 30 years of the energy chains is presented in Figure 3. From this figure it can be seen that the solar chains are by far the largest land consumers (especially SOLAR1 with Southern European solar radiation). The smallest land consumer is the FBR chain (this result would apply to any nuclear breeding concept). The large land requirements for the solar cases are mainly due to the heliostat fields of the STEC modules.

For the non-exclusive land use for the coal transportation, the total land requirements for a 900 km railway line or a slurry pipeline are presented in Table 2. The advantage of rail transportation is more evident if the land requirements per ton-kilometer are considered.

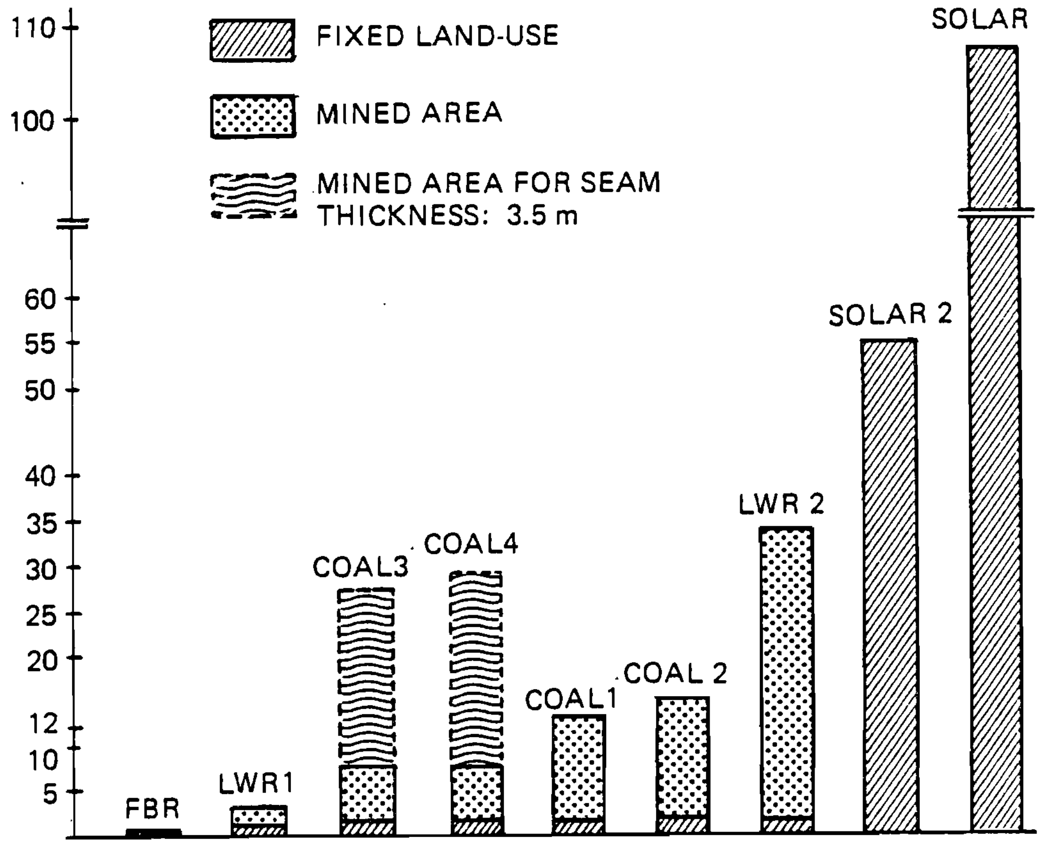

Figure 3. Land requirements for electricity producing chains (output: 6.1 Twh/yr) in km^2 (excluding non-exclusive land use for transportation).

The land impact of mining operations (area mined out or affected by subsidence) cumulated over 30 years is extremely important in the LWR2 case--33 km^2 or 97% of the total land requirements, and in the four coal cases--around 90% of total land requirements. As the coal chains with surface mining correspond to favorable geological conditions, the mining impact for a surface mine with only a 3.5 m seam instead of 9.2 m is also indicated in Figure 3.

The land requirements for the coal and nuclear chains cannot be compared directly with those of the solar chains. Although the cumulative mining impact, especially in the LWR2 case, already approaches the solar cases it is in fact a temporary impact, and after a period of between 5 and 10 years during which recultivation takes place the disturbed land can be re-used. At a given moment the real area worked or under recultivation represents only a fraction of the cumulative mining impact. One can therefore conclude that the solar chains have tremendous land requirements both in absolute and in relative terms compared to other energy chains, even when considering extreme cases like the LWR chain with uranium shale.

Manpower

The uncertainties with respect to new technologies (such as fluidized bed power plants or solar facilities) have led to the range of data presented for the manpower requirements for construction in Table 2. For the solar chains the construction manpower requirements are between 3 and 13 times as high as the figures for the other energy chains and are especially great in the SOLAR1 chain with European radiation.

For the solar chains the manpower requirements for operation are unknown especially for the large scale 100 MW units considered. The LMFBR chain (due to negligible mining impact and a less complex chain) is the smallest consumer of manpower for operation. In the coal chains two main conclusions can be drawn from the figures.

--the economy of manpower requirements in the coal chains with slurry pipeline transporation (COAL2 and COAL4);

--the significant impact of mining as reflected in the high manpower requirements for the mines and the much higher manpower productivity in surface mines.

The figures for the coal chains with underground mines correspond quite well to the actual average U.S. manpower productivity in underground mines, whereas the manpower figures for surface mines reflect the particularly favorable conditions of the mine chosen and, using the average U.S. productivity for strip mines, the figure would nearly double. The operational manpower requirements for the LWR2 chain, due to significant mining impact, are already of the same order of magnitude as the COAL4 chain with slurry transportation and strip-mined coal.

Materials

Table 3 presents the material requirements for the construction (metals and other materials such as concrete) and the operation (*non-energy materials* such as chemicals and limestone and *energy materials* such as coal or uranium). The cumulative material requirements during the lifetime of the energy chain are presented in Figure 4 for clarification. The two solar cases require large quantities of construction materials (steel: 0.6-1.7 million tons, concrete: 1.9-6.3 million tons, glass: up to 0.25 million tons) and are generally of the order of 10 to 40 times as high as for alternative systems. The range of data given in the LWR cases corresponds to the range of metal requirements for construction, depending on the type of reactor considered (U.S. or French data derived from a 900 MWe PWR unit [10,11]). If, on the other hand, the cumulative material requirements over the lifetime are considered (construction plus materials for operation) the

Table 3. Material requirements for energy chains producing 6.1 Twh/yr electricity (in 10^3 tons).

	METALS FOR CONSTRUCTION (Steel, Aluminum,...)	OTHER MATERIALS FOR CONSTRUCTION (Concrete, Sand,...)	NON ENERGY MATERIALS FOR OPERATION CUMULATED OVER 30 YEARS (Limestone, Chemicals,...)	ENERGY MATERIALS FOR OPERATION CUMULATED OVER 30 YEARS (Coal, Uranium)	TOTAL MATERIALS FOR 30 YEARS
COAL 1	43	151	8287	79000	87480
COAL 2	65	140	23566	84000	107770
COAL 3	44	142	>4000	79000	83186
COAL 4	67	130	23230	84000	107430
LWR 1	41.8–56.6	192.7	132	2700	~3100
LWR 2	43.4–58.2	>192.7	>132	119300	~119700
FBR	33	276.3	?	800	1103
SOLAR 1	844.3–1930.4	3298–6778	?	0	4142–8708
SOLAR 2	666.4–965.7	2005–3390	?	0	2671–4356

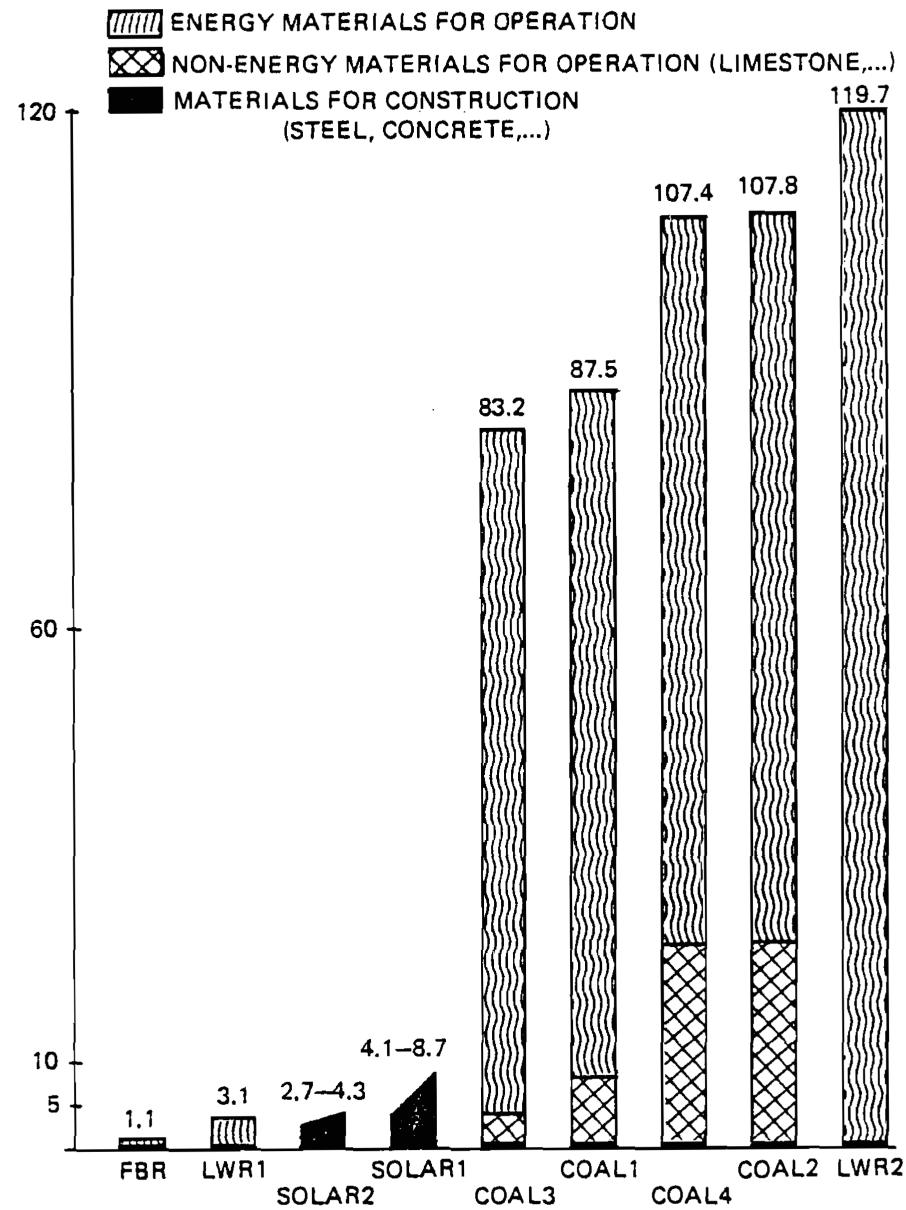

Figure 4. Cumulated material requirements - construction plus 30 years operation for energy chains producing 6.1 Twh/yr - in 10e6 tons

general trend of solar technologies (very high initial investment, low operating costs) is confirmed. As the solar cases consume practically no energy materials, the overall quantity of materials which have to be mined, processed and manipulated are much smaller than in the coal cases or in the LWR2 case. For the latter, 119 million tonnes of uranium shale have to be extracted, processed and the resulting wastes disposed of. This is comparable with the amounts of coal which have to be mined and transported in the four coal chains (between 79 and 84 million tonnes of coal for 30 years operation). In addition to the coal, the environmentally controlled coal chains with fluidized bed power plants require big quantities of limestone; in fact it should be noted that this figure could be drastically reduced by using a regenerative system.

CONCLUSION

From the study on energy chains for the production of electricity, it can be seen that the large scale use of the solar STEC technology, because of huge land requirements, would be possible only in favorable areas with high solar radiation. It can also conflict with other possible land uses (e.g. agriculture). In addition, since the material and manpower requirements for the construction of the heliostat fields are enormous this could create problems for the establishment of an appropriate infrastructure (housing for workers, transportation facilities for materials, etc.). On the other hand, there is certainly a potential for improving the WELMM requirements of the solar STEC technology through mass production and/or design and efficiency improvements.

The study has also revealed that the logical continuation of a long term nuclear strategy lies in the use of the FBR technology, because of the significant impacts of the materials to be handled and areas mined resulting from the use of lower grade ores when the present high-grade uranium resources are depleted. In the extreme case of using uranium shale of 60 ppm, the LWR technology approaches or even surpasses the impacts of coal electricity systems which produce the same amount of energy. For the coal chains one has to note that they reflect favorable mining conditions combined with high quality coal, the mining impact of these chains (especially important for manpower, land and energy materials required) is therefore subject to a wide range of variation (see for example the impact of the changing seam thickness of the land requirements for mining in Figure 3), especially if one were to consider Western European conditions. Therefore the impacts of mining operations will become even more important in the future especially in view of worsening geological conditions; the two most sensitive resources affected will be land and manpower. Advanced coal technology is not likely to relieve the impacts on natural resources (except for minor improvements in the water and direct energy requirements) but could significantly reduce the environmental impacts of the conventional coal-electric systems (see also Table 7 in the second part of this paper).

WELMM COMPARISON OF USEFUL ENERGY CHAINS

A reference demand on the useful energy level was defined and then alternative supply options for the production of the final energy required to meet this demand were considered. A competitive market therefore exists between various energy vectors (in our case electricity and gas) which provide the same service to the consumer, though with different quantities of final energy.

The useful energy output of the chains was defined as 0.65 Mtce and was distributed as follows:

72%	space heating	.468 Mtce
19%	hot water	.124 Mtce
7%	cooking	.045 Mtce
2%	drying	.013 Mtce
100%	total useful energy	.65 Mtce

This corresponds to the average distribution for residential useful energy consumption (excluding specific electricity e.g. for electric lighting and motors) in the United States [12]. For each of the energy uses defined above an efficiency of the end use appliances between final and useful energy was defined in order to determine the final energy requirements (Table 4). The supply options considered are based on precise projects in the U.S.A.; consisting of a coal mine (El Paso consol) with either an associated high BTU coal gasification complex of 280 million scft* per day or a fluidized bed coal-fired power plant (the electrical capacity equivalent to the gasification plant would be about 3000 MW). As a third alternative the import of liquefied natural gas (LNG) was considered. For the defined output of 0.65 Mtce useful energy of the chains only a fraction of the total capacity of the above

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* Standard cubic feet

Table 4. Main characteristics of useful energy chains (output: 0.65 Mtce useful energy/yr).

	COAL – ELECTRIC	SNG	LNG
EXTRACTION	STRIP MINE SEAM THICKNESS: 3.5 m STRIPPING RATIO: 5.42 (average)	COAL: 4620 kcal/kg	OFFSHORE GAS FIELD OFFSHORE PIPELINE
CONVERSION	1000 MW POWER PLANT LOAD FACTOR: 70% EFFICIENCY: 35.7%	100 MMSCFD* LURGI OXYGEN BLOWN GASI- FICATION WITH METHANATION PLANT – EFFICIENCY: 57.2%	LIQUEFACTION PLANT & EXPORT TERMINAL EFFICIENCY: 87%
TRANSPORT	——	——	LNG TANKER ROUND TRIP DISTANCE: 10150 Nautic Miles EFFICIENCY: 93.8%
SECONDARY CONVERSION	——	——	IMPORT TERMINAL & REGASIFICATION PLANT EFFICIENCY: 99.6%
TRANSPORT & DISTRIBUTION	HIGH VOLTAGE TRANSMISSION LINE 800 km & DISTRIBUTION NETWORK EFFICIENCY: 93%	GAS PIPELINE 800 km & DISTRIBUTION NETWORK EFFICIENCY: 93%	
FINAL ENERGY	0.7 Mtce	1 Mtce	
END USE EFFICIENCY: (72%) HEATING (19%) HOT WATER (7%) COOKING (2%) DRYING	 98% 91% 75% 65%	 66% 65% 40% 65%	
(100%) USEFUL ENERGY = 0.65 Mtce	92.6%**	64%**	
OVERALL EFFICIENCY USEFUL/PRIMARY (W/O EXTRACTION)	30.74%	34.03%	48.35%

*MMSCFD = million standard cubic feet per day

**Weighted average

mentioned projects is required; in the case of the coal-electric chain the required fraction corresponds to a 1000 MW coal-fired power plant. Therefore the results of the WELMM evaluation of this chain are comparable (minemouth versus load center electric conversion) to the coal chains presented in the previous chapter. Table 4 summarizes the main characteristics of the three chains studied, and a detailed description of them follows.

COAL ELECTRIC

To deliver 0.65 Mtce of useful energy, 0.7 Mtce final energy (electricity) are required (average end use efficiency of electricity : 92.6%). Taking into account the efficiencies for the transport and distribution of electricity and of the environmentally controlled atmospheric fluidized bed power plant, this results in 2.11 Mtce primary energy (coal input into the power plant).

SYNTHETIC NATURAL GAS (SNG)

In this chain 1.02 Mtce final energy in the form of gas have to be delivered to the consumer to provide 0.65 Mtce of useful energy (average end use efficiency of gas: 64%). 1.91 Mtce of primary energy in the form of coal have to be delivered to the Lurgi oxygen blown gasification plant (no by-product credit was included in the calculated efficiency of the plant--57.2%). Compared to the coal-electric option the quantity of primary energy required (coal which has to be produced from the same mine as in the coal-electric chain), is slightly lower. As both facilities (power plant and gasification plant) would be minemouth facilities, SNG as well as electricity have to be transported over an assumed distance of 800 km. A conservative assumption was made that the gas transporation and distribution system had the same efficiency as the electric one, although it is sometimes claimed to be more efficient [13].

LIQUIEFIED NATURAL GAS (LNG)

This is the most energy efficient chain, although it is also the most complex one. 1.02 Mtce gas have to be delivered as in the SNG chain to the consumer, but this requires only 1.34 Mtce of natural gas at the primary energy level. For the primary gas production it is assumed that the gas would be produced offshore and under extremely difficult conditions. For this purpose data on North Sea production platforms have been used as an example. For the liquefaction facilities data from the El Paso Algeria II project were used; the LNG chain considered would require about one tenth of the capacity of this one billion scft per day project. The LNG would be imported to the U.S.A. over a distance equivalent to that from the Middle East (round trip distance 10150 nautical miles). To be consistent with other chains we equally assumed a 800 km transportation distance from the import terminal to the consumer. This hypothesis also reflects the difficulty of installing LNG import terminals close to populated areas for safety reasons.

WELMM ANALYSIS

Table 5 gives an overview of the WELMM requirements for the three useful energy chains.

Water

The coal-electric chain is by far the largest water consumer. The huge water intake in the LNG chain corresponds to seawater intake. During the liquefaction process waste heat is discharged with seawater. For the regasification process the liquefied gas has to be heated; this can either be done by fuel fired boilers--which would result in a fuel consumption equivalent to 2% of the heating value of the LNG gasified--or by a more energy efficient method where seawater is cooled down in the process of LNG regasification (considered in this study). All this explains the significant seawater intake for the LNG chain.

Energy

From the energy point of view the LNG chain is the most efficient one--the conversion losses between primary and useful energy being only 0.32 Mtce compared to 0.89 Mtce for the SNG and 1.41 Mtce for the coal-electric chains. The coal-electric chain is the least efficient one, with an overall system efficiency of 30.74% (between primary and useful energy, the mining losses are not taken into account). With a pressurized fluidized bed system the thermal efficiency of the power plant could be increased from the 35.7% considered in the coal-electric chain to about 40%. The overall system efficiency would thus be similar to those of the SNG chain i.e. around 34%.

Land

As seen in Figure 5 the least land intensive chain is again the LNG one. The land requirements for harvesting the primary energy are zero (offshore gas field) and the fixed land use for export-import terminals, liquefaction and regasification plants etc. amount only to 0.33 km^2 compared to 2.5 km^2 for the coal-electric and 2.8 km^2 for the SNG chain. For the non-exclusive land use it is interesting to note the order of magnitude of the impact of the electricity transportation and distribution system. The coal electric chain requires between 43.1 and 55.5 km^2 right-of-way land for a 500 or 745 kV line over 800 km. Whereas the gas pipeline over the same distance requires only 12.1 km^2. The difference is accentuated if we consider that the coal electric chain requires 80% or 40% of the capacity of the 500 or 745 kV lines respectively [14]. Whereas the gas chain requires only 10% of the pipeline capacity considered.

Table 5. WELMM aspects of useful energy chains (output: 0.65 Mtce/yr useful energy).

			COAL–ELECTRIC	SNG	LNG
W	WATER INTAKE	10^6 m^3	15.8	4.5	50
	WATER CONSUMPTION		9.5	4.5	0
E	ENERGY LOSSES/YR	Mtce	1.41	0.89	0.33
L	LAND REQUIREMENTS:	km^2			
	EXCLUSIVE		2.5	2.8	0.3
	NON EXCLUSIVE*		43.1–55.5	12.1	12.1
	MINING/YEAR		0.9	0.8	0
M	MANPOWER	man-yrs			
	FOR CONSTRUCTION		4800–7200	3340	5050
	FOR OPERATION		560	580	300
M	ENERGY MATERIALS	10^6 tons/yr	3.2	2.9	0.8
	OVERBURDEN HANDLED		43.3	38.8	0
	OTHER MATERIALS HANDLED		2.2	1.4	NEGL.
	TOTAL MATERIALS MANIPULATED		48.7	43.1	0.8

*Total area required for electricity/gas transport over 800 km

It is interesting to note that the land requirements for transport for the load center electrical systems with long distance coal transport (presented in the previous chapter on electricity producing chains) are smaller than those of mine-mouth electrical conversion with long-distance electricty transport. The 43.1 to 55.5 km^2 at 80% or 40% share of capacity respectively, compare to 11.3 km^2 for rail transport (around 6% share of capacity) and 28.3 km^2 (about 10% share of capacity) for coal slurry transport over a similar distance.

The mining impact cumulated over 30 years in the coal-electric chain is slightly higher than in the SNG chain, due to the smaller overall systems efficiency (more coal has to be mined out).

Manpower

Table 5 presents the manpower requirements for construction and operation of the three chains considered. For the construction manpower requirements in the case of the coal-electric chain a range of data has been presented. This is due to the fact that for the fluidized bed power plant the available data [14] indicate higher manpower requirements when compared to conventional coal-fired power plants.

Secondly, the manpower requirements for the construction of the electricity transportation and distribution system (4000 man-years or more--see [14],[15] for example) are very high compared to the manpower requirements for the construction of the gas pipeline and distribution system (around 800 man-years, see [14] for example). As the electricity distribution system is generally more decentralized and therefore more construction-manpower intensive than gas distribution systems, and for the purpose of our comparison on the useful energy level, the same degree of decentralization would be required for both energy vectors. The data available are affected by too much uncertainty to allow for definitive conclusions without a detailed analysis of alternative transportation and distribution systems. The range of data presented therefore puts the construction manpower requirements into a relative context for comparison with alternative energy chains, rather than representing reliable absolute values.

For operational manpower requirements one can conclude that the LNG chain is the least manpower-intensive one, whereas for the coal based chains no difference in the operational manpower has been found.

Materials

Table 6 presents the material requirements for the construction of the three alternative useful energy chains. The LNG and SNG chains are generally more construction-material-intensive than the coal-electric chain, due to more complex technology.

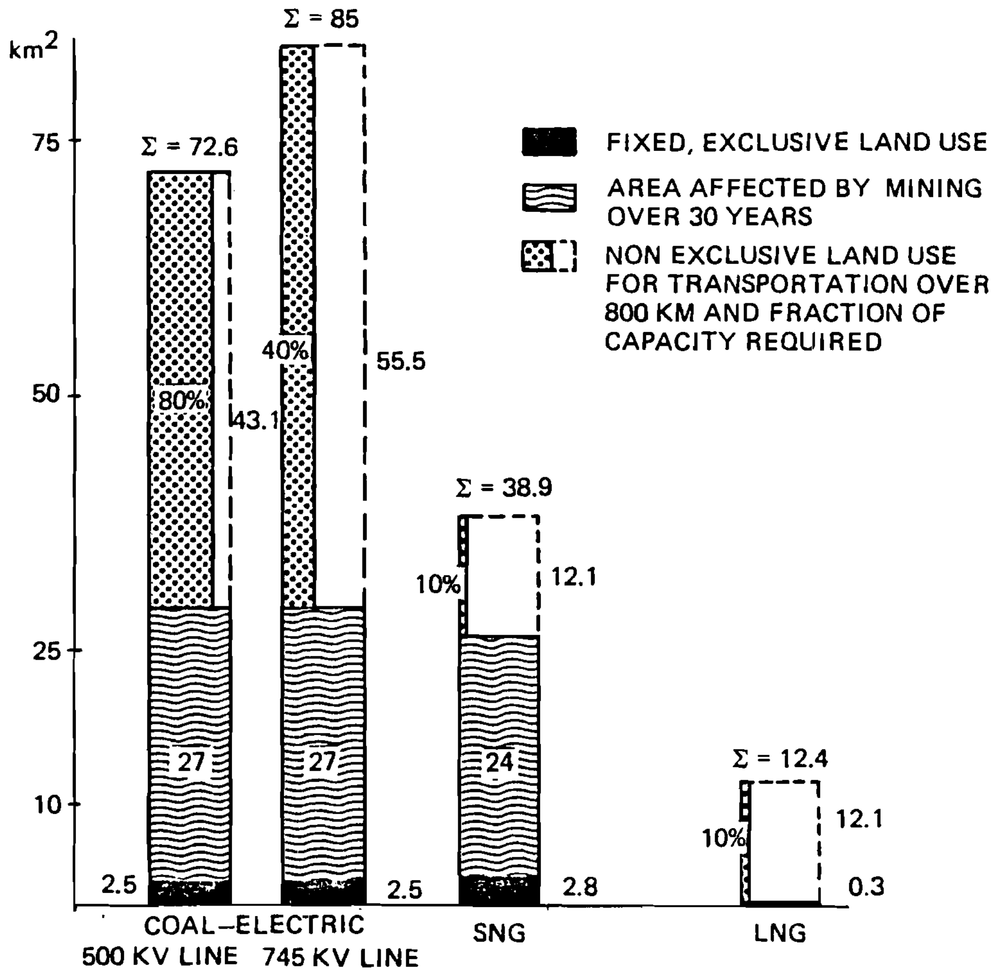

Figure 5. Land impacts of useful energy chains producing 0.65 Mtce (in km^2).

	COAL-ELECTRIC	SNG	LNG
STEEL	59556	98036	97305
OTHER METALS	13488	2716	614
TOTAL METALS	73044	100752	97919
OTHER MATERIALS: CONCRETE	153400	96067	78613

Table 6. Material requirements for the construction of useful energy chains, in tons (output: 0.65 Mtce/yr useful energy).

These observations change drastically if the material aspects for the operation of the chains as presented in Table 5 are considered. The energy materials and other materials handled are practically negligible in the LNG chain (0.8 million tons per year); whereas for the coal-based systems, in addition to the coal required (between 2.9 and 3.2 million tons/year),* additional materials (like overburden) have to be mined, manipulated and disposed of at the coal mine. The total mass of materials handled each year thus amounts to 43.1 to 48.7 million tons and accentuates the advantage of the LNG chain (only 0.8 million tons handled per year).

CONCLUSION

To conclude we can summarize the above discussion on the WELMM requirements of useful energy chains in two main areas. The first one deals with the advantages of the LNG chain compared to the SNG or coal-electric system.† Secondly, the coal-electric chain described in this section can be compared to that described in the previous section. This results in a comparison of minemouth versus load center electric conversion.

The key question for the useful energy chains is certainly that of the energy efficiency. LNG (the most efficient technology) generally shows the lowest resource requirements. In considering the two coal-based systems the advantage of the SNG chain over the coal-electric one in terms of energy efficiency is reflected in the WELMM analysis for the land and material impacts. As already mentioned, the efficiency of the power plant

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*The coal requirements for the coal-electric chain considered are also higher than those of the coal chains presented in the previous section (3.2 million tons/year compared to 2.6 to 2.8 million tons/year) due to the lower heat content of the coal used in the project considered [16].

†From the resource management (or WELMM) point of view.

could be increased in order that the overall coal-electric system efficiency is equal to that of the SNG chain. On the other hand the assumptions for the efficiency of the SNG system were rather conservative (both for the gas transport and distribution and for the gasification plant) so there also appears to be a possibility for increasing the systems efficiency of the SNG chain which would then preserve its slight advantage, in terms of energy efficiency, land and material requirements, over the coal-electric chain. The huge quantities of materials manipulated (coal, overburden, wastes, etc.) every year in the coal-based systems are also reflected in other WELMM parameters (i.e. manpower for operation and land requirements for mining). We can therefore conclude that the LNG chain is the least resource intensive chain of the three alternatives considered. The SNG chain shows a slight advantage in the resource requirements (especially important for water and non-exclusive land use) over the alternative coal-electric system.

In comparing the coal-electric system with electricity production near the mine and then long-distance transportation of electricity to the main consuming areas with the coal electric systems described in the previous section, where coal is transported over long distances to the powerplant located close to the demand areas, one can conclude that the load center electric conversion shows more favorable results than the minemouth electric conversion. The high voltage transmission lines are very investment-intensive in terms of construction materials ($73\ 10^3$ tons of metals compared to 43 to $67\ 10^3$ tons for rail or coal slurry transporation over a slightly longer distance). In addition the land requirements--although non-exlusive in nature--are, for the transmission lines, an order of magnitude higher than for the rail lines or slurry pipelines.

The WELMM analysis can be enlarged by including other criteria such as economic or environmental considerations. Economic data for the concrete case of the useful energy chains have the tendency to be misleading as the cost estimates for new technologies (i.e. those not yet implemented on a commercial scale) are affected by too much uncertainty. In addition the price of imported LNG cannot be predicted with the desirable degree of accuracy: in many countries (e.g. in Europe) the LNG prices as fixed in the contracts are even not published. We therefore decided not to present economic data but rather to refer to the publications already mentioned which give details on cost comparisons [12,13]. These data reflect general tendencies rather than accurate estimates and have to be understood in the specific context for which they have been elaborated. Nevertheless it is worth noting that the WELMM evaluation results in the same trend as economic analysis: the LNG and, to a lesser extent, the SNG chain, although capital-intensive (as reflected in the manpower and material requirements for construction) are more economical (also in the sense of the natural resources required) to operate.

For an environmental analysis, some aspects are included explicitly in the WELMM approach (i.e. water, land and materials including wastes). Apart from the environmental advantages of using natural gas (no mining impact, low air emissions), environmental data increase the advantage of SNG over electricity, produced even with "environmentally controlled" technologies like fluidized bed power plants. Although there is a wide range for air emission data (depending essentially on the quality of coal used which is unfortuantely not always explicitly stated in environmental studies). Table 7 presents a range of air emission figures for the SNG and "environmentally controlled" electricity generation plants required for the useful energy chains.

Synthetic natural gas production causes considerably lower air emission than coal-electric systems. Other environmental advantages, like smaller water requirements, slightly smaller mining impacts and reduced land impacts, stress the advantage of SNG over the coal-electric system.

It can therefore be concluded that the study on useful energy chains has revealed that liquified natural gas (LNG) has a clear advantage in terms of energy efficiency, most resource requirements and environmental impacts. When comparing the use of coal either for electricity generation or for the production of synthetic natural gas (SNG) the slight advantage of the latter in terms of energy efficiency, land, manpower and material requirements is accentuated when considering environmental impacts like air emissions.

Table 7. Summary of environmental aspects coal gasification and electricity

	COAL–GASIFICATION[1]	COAL ELECTRICITY ENVIRONMENTALLY CONTROLLED[2] SCRUBBERS	FLUIDIZED BED
AIR EMISSIONS IN TONS/YEAR			
PARTICULATES	250 (110–250)	1000–2000	270–?
SO_2	730* (320–2000)	4000–4600	3200–?
NO_x	750* (750–4100)	20000–22700	3600–3900
CO	130 (130–230)	1100	550–?
HC	40 (40–70)	330	?
SOLID WASTES IN 10^3 TONS/YR	402* (164–402)	400–700	>220–1000

Notes:

[1] Figures marked with an asterix were derived from the El Paso Consol Project [16]; all other figures indicate the range of data as compiled in [17].

[2] Figures based on low sulfur western coal (similar to El Paso coal); solid waste figures vary depending if a regenerative limestone system is used or not. (References: [12], [17], [18]).

GENERAL CONCLUSION

The type of information that is obtained from a WELMM analysis may provide decision makers with additional knowledge of the natural resource aspects of energy strategies. This is especially important since physical data are not likely to fluctuate as widely as monetary data. In fact, when prices or financial data are either lacking or uncertain (which is often the case for long-term strategies and new technologies) it is useful to express the natural (and human) resources in physical terms or, as we say, in "WELMMITE" requirements and to emphasize their systems implications and interrelations. The results of the WELMM approach naturally reflect the general tendencies of technologies derived from economic analysis: i.e. capital intensive technologies such as the solar STEC or the LNG chains have a strong impact on natural and human resources in the construction phase whereas they are more economical to operate in terms of resources. Nevertheless, some constraints or bottlenecks appear in a WELMM analysis which would not be obvious in an economic one. A careful decision-making analysis should thus include the different aspects represented by the economic impacts, the WELMM impacts, the environmental impacts etc. (An attempt has been made in this paper to give some information on environmental impacts as well).

Obviously the method used (although it is not used exclusively but rather as an additional tool) and the type of applications presented in this paper have their limits. The comparison of electricity producing chains did not take into account that some resources (e.g. solar) are more appropriate for specific uses (e.g. low grade heat). The example of useful energy chains tried to take into account the competition of various energy vectors at the final energy level, but the number of alternative chains studied would have to be increased, including decentralized solar, centralized nuclear district heating and other systems.

The main disadvantage of the energy chain comparisons is that they represent specific examples based on rather small-scale projects and do not allow for the drawing of definite conclusions about their feasibility on the regional or national scale. They therefore represent only one step towards a more systematic analysis of energy supply options. Different supply schemes, representing different supply options have thus been studied at IIASA and the first results concerning the resource requirements of these "energy scenarios" have already been obtained [19]. The study of the "scenarios" focussed, as a first step, on the evaluation of four monoenergetic supply options based on different primary energy forms (coal, nuclear, oil/gas and solar) for a predefined reference demand on the useful or final energy level on a national scale. Detailed energy chains for the various end use categories (specific electricity, low grade heat, motor fuels etc.) and on a large-scale were elaborated. A precise geographical situation for the siting of energy facilities and for the transportation and distribution of energy was considered thus allowing more realistic scenarios on long-term energy supply options. Resource requirements for the various supply strategies are thus considered within a framework of specific locations and forms and can then be checked with their relative scarcity at a national or global level.

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APPENDIX

This appendix gives more detailed data on the WELMM evaluation of the nuclear and solar electricity generating chains.

Tables A-1 and A-2 :	Detailed data on the mining impacts for the three nuclear electricity generating chains are shown as a percentage (A-1) and as absolute values (A-2).
Table A-3	WELMM requirements for the construction of three designs of 100 MWe STEC's are shown. For our electricity generating chains SOLAR 1, located in France, would require 28 100 MW STEC modules (hypothesis 2); SOLAR 2, located in Southern California, would require 14 100 MW STEC modules (MITRE data [21]).

A-1. Percentage of total chain requirements at various steps of three nuclear electricity chains

	MINING			UPGRADING, REPROCESSING WASTE DISPOSAL...			POWER PLANT			TOTAL CHAIN		
	LWR1	LWR2	LMFBR	LWR1	LWR2	LMFBR	LWR1	LWR2	LMFBR	LWR1	LWR2	LMFBR
Water Operation (m^3)/yr	-	-	-	2.3%	3.3%	.2%	97.7%	96.7%	99.8%	29.4 $10^6 m^3$	29.7 10^6	19.4 $10^6 m^3$
Energy Operation												
fossil fuels (kcal)/yr	29.2%	39.6/3.5%	-	64.5%	55/96%	?	6.3%	5.4/0.5%	?	50.7 10^9	60/585 10^9	?
electricity (kwh)/yr	.6%	15.3/8.4%	-	99.4%	84.7/91.6%	?	-	-	-	293 10^6	344/396 10^6	?
Land												
fixed use (km^2)	0.3/0.4%	?	-	47.5/32.3%	47/31%	13.8%	52.2/67.3%	53/69%	86.2%	1/1.5 km^2	1/1.5	1.45
area affected by disturbance or subsidence (km^2)/yr	100%	100%	100%	-	-	-	-	-	-	0.07 km^2	1.1	0.007
Materials (mt)												
Construction												
steel	2.5/1.8%	6.2/4.6%	-	15/11.1%	14.5/10.8%	4.2%	82.5/87%	79.4/84.5%	95.7%	42,000/ 56,000	43,000/ 57,500	33,000
aluminum	11.6/6.6%	-	-	60.8/34.4%	68.8/36.9%	3.9%	27.6/59%	31.2/63.1%	96.1%	65/115	58/108	59
concrete	-	-	-	6.6%	6.6%	-	93.4%	93.4%	100%	193,000	193,000	272,000
Operation												
chemicals/yr	?	?	?	100%	100%	?	-	-	?	4400	4400	?
solid waste or overburden moved/yr	95.4%	?	-	4.6%	100%	100%	-	-	-	0.3/1.9 10^6	4 10^6	0.025 10^6
Manpower (my)												
Construction	1.4%	2.4%	-	9.8%	9.7%	2.8%	88.8%	87.9%	97.1%	6755	6827	7462
Operation/year	21.7%	58.9%	1.3%	33.4%	17.4%	26.8%	45%	23.7%	71.9%	245	464	142

- = impact negligible, mt = metric tons
? = impact unknown, my = man years

N.B. Percentages may not total 100% since they have been rounded .

Table A-2. WELMM assessment of three nuclear-electric chains

	MINING			UPGRADING, REPROCESSING WASTE DISPOSAL			POWER PLANT			TOTAL CHAIN		
	LWR1 .208%U308	LWR2 .007%U308	LMFBR .007%U308	LWR1	LWR2	LMFBR	LWR1	LWR2	LMFBR	LWR1	LWR2	LMFBR
WATER OPERATION intake in $10^6 m^3$	0.005	0.0056	.00034	.671	.971	.036	28.7	28.7	19.4	29.376	29.67	19.44
ENERGY OPERATION												
motor fuel/yr, process fuel/yr } 10^9kcal	14.8	20.3 - 23.55[a] 33.4 - 52.5[a]	0.15	32.66	>32.66-561.68[c] >291.37	NA	3.2	3.2	NA	50.66	>59.4-585.2[a]	NA
electricity/yr 10^6kwh	1.632		.335	291.37	-362.23[c]	NA	0	0	0	293	>343.9-395.6[c]	NA
LAND												
fixed use km^2	0.008[b] 0.0027/0.00645[a]	NA	NA	.45 (.2p)	>.45 (.2p)	.2 NA	.5-1 (.4p)	.5-1 (.4p)	1.25 NA	.958/1.485 (.6p)	>.95/1.45 (.6p)	>1.45 (>.6p)
disturbance or subsidence/year km^2	.0688[b] 0.0288/0.0323[a]	1.1	.0072	-	-	-	-	-	-	.0688[b] 0.0288/0.0323[a]	1.1	.0072
MATERIALS												
CONSTRUCTION												
steel mt	1020	2657.7	17	6231.3	>6231.3	1382	34141/48600	34141/48600	31550	41392/55851	43030/ 57489	32949
aluminium mt	7.6	NA	NA	33.7	>39.7	2.3	18/68	18/68	57	>65.3/115.3	>57.7/107.7	>59.3
copper mt	NA	NA	NA	NA	NA	NA	366/694	366/694	NA	366/694	366/634	NA
cement mt	-	NA	NA	-	-	-	-	-	4295	-	-	4295
concrete mt	1.78	NA	NA	12740	>12740	NA	180000	180000	272000	192742	>192740	272000
OPERATION												
chemicals mt	NA	NA	NA	4400	>4400	NA	NA	NA	NA	>4400	>4400	NA
solid waste mt	NA	NA	NA	91469	3.97 10^6	25441	-	-	-	31469	>4 10^6	25441
overburden moved & waste rock 10^6mt	.255/1.905	NA	NA	0	0	0	0	0	0	.255/1.905	NA	NA
MANPOWER, man-years												
CONSTRUCTION	91.66	163.86	1	663.6	>663.6	211.5	6000	6000	7250	6755.26	>6827.5	7462.5
OPERATION/year	53	273.5	1.8	81.6	> 80.6	37.9	110	110	101.8	244.6	464.1	141.5

[a] only underground mines/surface mines
[b] data source WASH-1284 [20]
[c] data source Bieniewski [8]
- negligible
(p) permanent land use
NA data not available

Table A-3. Estimates for the requirements for construction of three different designs of 100 MWe STEC, producing electricity for an intermediate demand (6 hours storage)

	MITRE [21]	ACCORDING TO MITRE [21]		ACCORDING TO THEMIS [22]
LOCATION	CALIFORNIA	FRANCE		FRANCE
DIRECT INSOLATION	3000 KWH/M^2/YR	1500 KWH/M^2/YR		1500 KWH/M^2/YR
ANNUAL PRODUCTION	438 GWH	438 GWH		438 GWH
WELMM REQUIREMENTS		HYPOTHESIS 1	HYPOTHESIS 2	
GLASS (10^3 KGS/MWE)	45 - 91	90 - 180	90 - 180	100
CONCRETE	1361 - 2268	2229 - 3136	2722 - 4536	1673
STEEL	454 - 635	581 - 762	908 - 1270	1283
COPPER	4.5 - 9	4.5 - 9	9 - 18	N.A.
ALUMINIUM	18 - 45	18 - 45	36 - 90	N.A.
INSULATION	18 - 36	18 - 36	36 - 72	N.A.
PLASTICS	4.5 - 18	9 - 36	9 - 36	N.A.
SILVER	0.006 - 0.008	0.012 - 0.024	0.012 - 0.024	N.A.
MISC.	4.5 - 9	9 - 18	9 - 18	N.A.
TOTAL MATERIALS (10^3 KGS/MWE)	1910 - 3111	2959 - 4223	3819 - 6221	
TOTAL MANPOWER FOR THE PLANT (MAN YRS)	1700	2200	3400	N.A.
TOTAL LAND FOR THE PLANT (HA)	388	776	776	N.A.

HYPOTHESIS 1 : A FIELD OF HELIOSTATS TWICE THAT OF CALIFORNIA
HYPOTHESIS 2 : COMPARED TO CALIFORNIA, TWICE AS MANY PLANTS FOR FRANCE